On coordinate distances to type Ia supernovae and radio galaxies

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Abstract

The quantum model of the homogeneous and isotropic universe predicts logarithmic-law dependence of coordinate distance to source on redshift z which is in good agreement with type Ia supernovae and radio galaxies observations for the redshift range $z = 0.01 - 1.8$. A comparison with phenomenological models with dark energy in the form of cosmological constant and without dark energy component is made. Fluctuations of the cosmological scale factor about its average value which can arise in the early universe produce accelerating or decelerating expansions of space subdomains containing separate sources with high redshift whereas the universe as a whole expands at a steady rate.

Key words: quantum cosmology, coordinate distance, type Ia supernovae, radio galaxies, quantum fluctuations
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1 Introduction

The high-redshift type Ia supernova (SN Ia) observations [1, 2, 3] can be explained by an accelerating expansion of the present-day universe [1, 2, 4, 5, 6]. Such conclusion assumes that observed dimming of the SNe Ia is hardly caused by physical phenomena non-related to overall expansion of the universe as a whole (see e.g. Refs. [3, 7] for discussion and review). Furthermore it is supposed that matter component of energy density in the universe ρ_M varies with the expansion of the universe as a^{-3} (i.e. it has practically vanishing pressure, $p_M \approx 0$), where a is the cosmological scale factor, while mysterious cosmic fluid (so-called dark energy [8, 9]) is describes by the equation of state $p_X = w_X \rho_X$, where $-1 \leq w_X \leq -\frac{1}{3}$ [4, 5]. In the models with the cosmological constant (ΛCDM) one has $w_X = -1$ [3, 4, 5], while in general case w_X may vary with time (models with quintessence) [5, 6]. Even if regarding baryon component one can assume that it decreases as a^{-3} (pressure of baryons may

be neglected due to their relative small amount in the universe), for dark matter (whose nature and properties can be extracted only from its gravitational action on ordinary matter) such a dependence on the scale factor may not hold in the universe taken as a whole (in contrast to local manifestations e.g. in large-scale structure formation, where dependence a^{-3} may survive). Since the contribution from all baryons into the total energy density does not exceed 4 % [10], the evolution of the universe as a whole is determined mainly by the properties of dark matter and dark energy. The models of dark energy [4, 5, 8] show explicitly unusual behaviour of this component during the expansion of the universe.

In the present paper we notice that the quantum model of the homogeneous and isotropic universe filled with primordial matter in the form of the uniform scalar field proposed in Refs. [11, 12] allows to explain the observed coordinate distances to SNe Ia and radio galaxies (RGs) in wide redshift range.

2 Coordinate distance to source

According to quantum model [11, 12] the universe can be both in quasistationary and continuum states. Quasistationary states are the most interesting, since the universe in such states can be characterized by the set of standard cosmological parameters [12]. The wavefunction of quasistationary state as a function of a has a sharp peak and it is concentrated mainly in the region limited by the barrier formed by the interaction between the gravitational and scalar fields. It can be normalized (cf. Ref. [13]) and used in calculations of expectation values of operators corresponding to observed parameters within the lifetime of the universe.

If one considers the average value of the scale factor $\langle a \rangle$ in the state with large quantum numbers, enumerating the states of gravitational (n) and scalar (s) fields, as determining the scale factor in classical approximation, then from functional equation of quantum model for the wavefunction [11, 12] follows the Einstein-Friedmann equation in terms of average values

$$\left(\frac{1}{\langle a \rangle} \frac{d\langle a \rangle}{dt} \right)^2 = \langle \rho \rangle - \frac{1}{\langle a \rangle^2}, \tag{1}$$

where

$$\langle \rho \rangle = \gamma \, \frac{M}{\langle a \rangle^3} + \frac{E}{\langle a \rangle^4} \tag{2}$$

is the mean total energy including the contribution from matter and radiation in the universe in the states with $n \gg 1$ and $s \gg 1$, and length and density are measured in units $l_P = \sqrt{2G/(3\pi)}$ and $\rho_P = 3/(8\pi G l_P^2)$ respectively. The coefficient $\gamma = 193/12$ arises in calculation of expectation value for the operator of energy density of scalar field and takes into account its kinetic and potential terms. The value

$M = m\left(s + \frac{1}{2}\right)$, where m is a mass of elementary excitation of the scalar field[1], s counts the number of these excitations, can be treated as a quantity of matter/energy in the universe. There is the following relation between the parameters of the universe [11, 12]

$$E = 4\langle a\rangle \left[\langle a\rangle - M\right]. \tag{3}$$

In matter dominated universe $M \gg E/(4\langle a\rangle)$ and from Eqs. (2) and (3) it follows that the quantity of matter/energy M and the mean energy density $\langle\rho\rangle$ in the universe taken as a whole (i.e. in quantum states which describe only homogenized properties of the universe) satisfy the relations

$$M = \langle a\rangle, \qquad \langle\rho\rangle = \frac{\gamma}{\langle a\rangle^2} \tag{4}$$

which agree with the data of observations in the present-day universe. Substitution of Eq. (4) into (1) leads to the density parameter $\Omega = 1.066$. It means that the universe in highly excited states is spatially flat (to within about 7 %). This value of Ω agrees with existing astrophysical data for the present-day universe [14, 15, 16].

From (1) and (4) we find the Hubble constant $H = (1/\langle a\rangle)\, d\langle a\rangle/dt$ as a function of cosmological redshift $z = (a_0/\langle a\rangle) - 1$, where a_0 is a scale factor at the present epoch,

$$H(z) = H_0\,(1 + z). \tag{5}$$

Then the dimensionless coordinate distance $H_0\, r(z)$ to source at redshift z, where $r(z) = (1+z)^{-1}\, d_L$, d_L is the luminosity distance, (see Refs. [4, 7, 17, 18]) for a flat universe obeys the logarithmic law

$$H_0\, r(z) = \ln(1 + z). \tag{6}$$

The dimensionless coordinate distances to the SNe Ia and RGs obtained in Ref. [17] from the observational data (solid circles and boxes) and our result (6) (solid line) are shown in Figs. 1 - 3. The ΛCDM-model with $\Omega_M = 0.3$ (matter component) and $\Omega_X = 0.7$ (dark energy in the form of cosmological constant) and the model without dark energy ($\Omega_M = 1$) are drawn for comparison. In Fig. 2 the SNe Ia data in the interval $z = 0.1 - 0.8$ are shown on a larger scale. Among the supernovae shown in Figs. 1 and 2 there are the objects with central values of coordinate distances which are better described by the ΛCDM-model (e.g. 1994am at $z = 0.372$; 1997am at $z = 0.416$; 1995ay at $z = 0.480$; 1997cj at $z = 0.500$; 1997H at $z = 0.526$; 1997F at $z = 0.580$), the law (6) (e.g. 1995aw at $z = 0.400$; 1997ce at $z = 0.440$; 1995az at $z = 0.450$; 1996ci at $z = 0.495$; 1996cf at $z = 0.570$; 1996ck at $z = 0.656$) and the model with $\Omega_M = 1$ (1994G at $z = 0.425$; 1997aj at $z = 0.581$; 1995ax at $z = 0.615$; 1995at at $z = 0.655$). The RG data [17] demonstrate the efficiency of the model (4) as well (Fig. 3). The quantum model predicts the coordinate distance to SN

[1] As usual it is assumed that the scalar field oscillates with a small amplitude around the equilibrium vacuum value due to the quantum fluctuations.

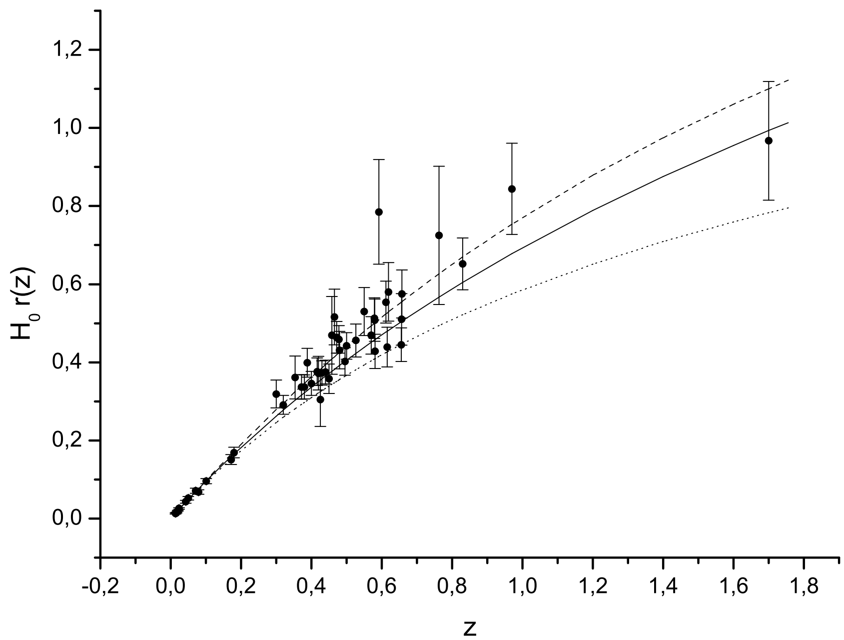

Figure 1: Dimensionless coordinate distances $H_0\,r(z)$ to supernovae at redshift z. The observed SNe Ia are shown as solid circles. The model (4) is drawn as a solid line. The ΛCDM-model with $\Omega_M = 0.3$ and $\Omega_X = 0.7$ is represented as a dashed line. The model with $\Omega_M = 1$ is shown as a dotted line.

1997ff at $z \sim 1.7$ which is very close to the observed value (see Fig. 1). In the range $z \leq 0.2$ three above mentioned models give in fact the same result.

The density $\langle \rho \rangle$ (2) contains all possible matter/energy components in the universe. Let us separate in (2) the baryon matter density equal to $\Omega_B \approx 0.04$ [15, 16] which makes a small contribution to the matter density $\Omega_M \approx 0.3$ [3]. If we assume that the baryon density varies as $\rho_B \sim a^{-3}$, while the remaining constituents of density effectively decrease as a^{-2}, then the value $H_0 r(z)$ calculated in such a model will practically coincide with the coordinate distance shown in Fig. 1 as a solid line.

In Ref. [7] a conclusion is drawn that the model of dark energy with $w_X = -\frac{1}{3}$ implying $\rho_X \sim a^{-2}$ agrees with the recent CMB observations made by WMAP as well as with the high redshift supernovae Ia data. Such a universe is decelerating. In our quantum model the total dark matter/energy in the states which describe only homogenized properties of the universe varies effectively as a^{-2}. In terms of general relativity it means that its negative pressure compensates for action of gravitational

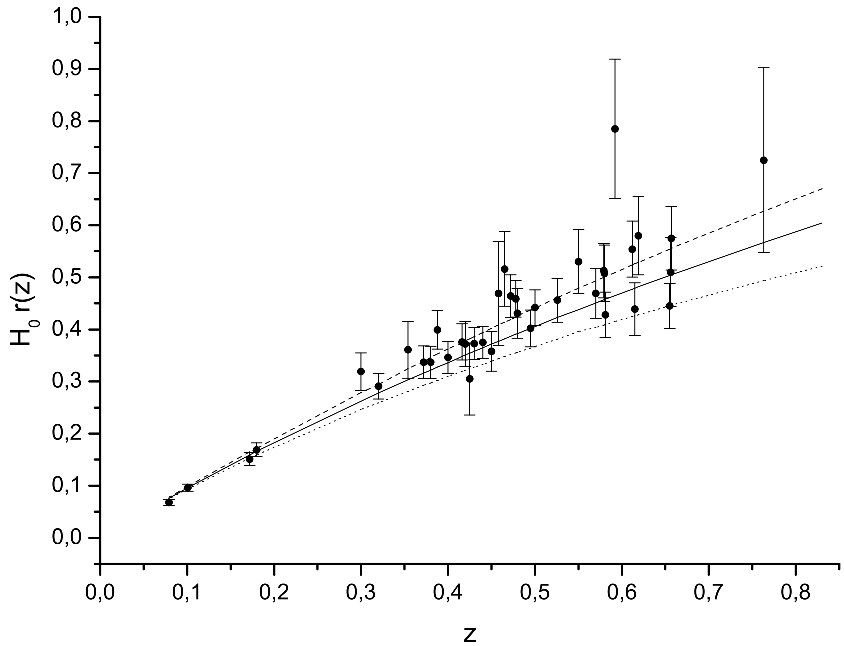

Figure 2: The same as in Fig.1 in the interval $z = 0.1 - 0.8$ on a larger scale.

attraction and the universe as a whole expands at a steady speed.

3 Quantum fluctuations of scale factor

Deviations of $H_0\, r(z)$ from the law (6) towards both larger and smaller distances for some supernovae can be explained by the local manifestations of quantum fluctuations of scale factor about $\langle a \rangle$ which arose in the Planck epoch ($t \sim 1$) due to finite widths of quasistationary states. As it is shown in Refs. [11, 12] such fluctuations can cause the formation of nonhomogeneities of matter density which have grown with time into the observed large-scale structures in the form superclusters and clusters of galaxies, galaxies themselves etc. Let us consider the influence of mentioned fluctuations on visible positions of supernovae.

The position of quasistationary state E_n can be determined only approximately, $E_n \to E_n + \delta E_n$, where $|\delta E_n| \sim \Gamma_n$, Γ_n is the width of the state. The scale factor of the universe in the n-th state can be found only with uncertainty,

$$\langle a \rangle \to \langle a \rangle + \delta a, \tag{7}$$

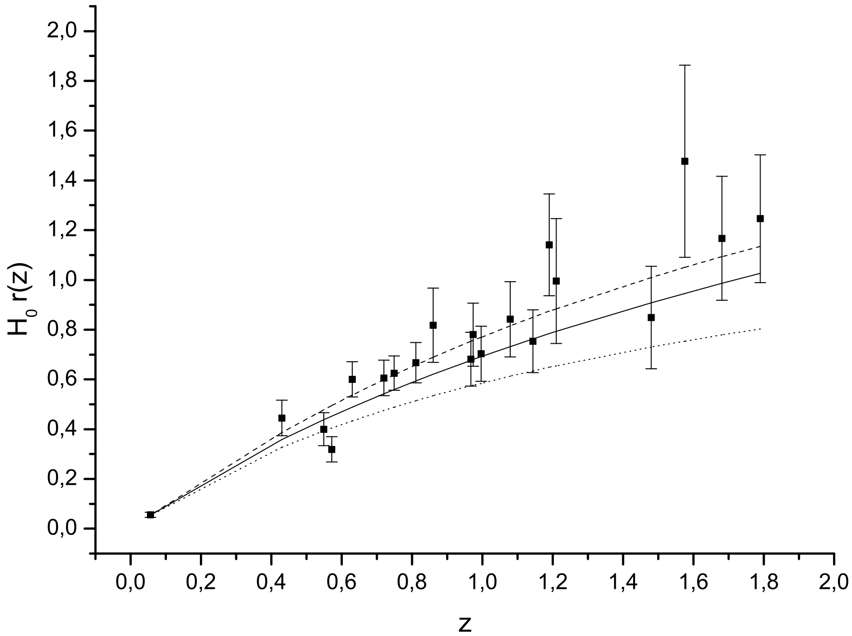

Figure 3: Dimensionless coordinate distances $H_0\,r(z)$ to radio galaxies at redshift z. Radio galaxies are shown as solid boxes. The rest as in Fig.1.

where the deviation $\delta a \gtrless 0$ is determined by both the value δE_n and the time of its formation [11, 12]. Since Γ_n is exponentially small for the states $n \gg 1$, the fluctuations δE_n in the early universe are the main source for δa. The calculations demonstrate that the lowest quasistationary state has the parameters $E_{n=0} = 2.62$ and $\Gamma_{n=0} = 0.31$ (in dimensionless units). The radius of curvature is $\langle a \rangle_{n=0} \sim 1$, while the lifetime of such a universe is $\tau \sim \Gamma_{n=0}^{-1} \sim 3$. Within the time interval $\Delta t \leq 3$ the nonzero fluctuations of scale factor with relative deviation equal e.g. to

$$\begin{aligned}
\left|\frac{\delta a}{\langle a \rangle}\right| &\lesssim 0.022 \quad \text{at} \quad \Delta t = 1, \\
\left|\frac{\delta a}{\langle a \rangle}\right| &\lesssim 0.040 \quad \text{at} \quad \Delta t = 2, \\
\left|\frac{\delta a}{\langle a \rangle}\right| &\lesssim 0.077 \quad \text{at} \quad \Delta t = 3
\end{aligned} \tag{8}$$

can be formed in the universe. Such fluctuations of the scale factor cause in turn the fluctuations of energy density which can result in formation of structures with

corresponding linear dimensions under the action of gravitational attraction. For example, for the current value $\langle a \rangle \sim 10^{28}$ cm the dimensions of large-scale fluctuations $\delta a \lesssim 70$ Mpc, $\delta a \lesssim 120$ Mpc, and $\delta a \lesssim 200$ Mpc correspond to relative deviations (8). On the order of magnitude these values agree with the scale of superclusters of galaxies. Let us note that the probability of the fluctuations which can yield the scale of nonhomogeneities of the matter density ~ 200 Mpc in visible part of the universe is small because of large probability of tunneling of the universe into the region of the continuous spectrum from the lowest state with $n = 0$ at $\Delta t = 3$.

If one assumes that just the fluctuations δa cause deviations of positions of sources at high redshift from the law (6), then it is possible to estimate the values of relative deviations $\delta a / \langle a \rangle$ from the observed values $H_0 \, r(z)$. The fluctuations of scale factor (7) generate the changes of coordinate distances,

$$H_0 \, r(z) = \ln \left[\left(1 + \frac{\delta a}{\langle a \rangle} \right)^{-1} (1 + z) \right]. \tag{9}$$

Table 1: Relative deviations $\delta a / \langle a \rangle$ for some type Ia supernovae

Group	SN Ia	z	$H_0 \, r(z)$ [17]	$\delta a / \langle a \rangle$
1	1994am	0.372	0.337	- 0.020
	1997cj	0.500	0.442	- 0.036
	1997H	0.526	0.456	- 0.033
	1997F	0.580	0.508	- 0.049
	1997R	0.657	0.575	- 0.068
	1997ck	0.970	0.844	- 0.153
2	1997ff	1.700	0.967	+ 0.027
3	1994G	0.425	0.305	+ 0.050
	1997aj	0.581	0.428	+ 0.031
	1995ax	0.615	0.439	+ 0.041
	1995at	0.655	0.445	+ 0.061
4	1996J	0.300	0.319	- 0.055
	1995ba	0.388	0.399	- 0.069
	1995ar	0.465	0.516	- 0.095
	1997K	0.592	0.785	- 0.274

Relative deviations $\delta a / \langle a \rangle$ calculated from observed coordinate distances (central values) for some type Ia supernovae are shown in Table 1. The supernovae better described by the ΛCDM-model are placed in Group 1. All shown supernovae have negative relative deviations with absolute values within the limits of (8). The only exception is SN 1997ck at $z = 0.970$. The supernova 1997ff at $z \sim 1.7$ which has

the coordinate distance close to the prediction of the quantum model (6) is located in Group 2. It has small positive relative deviation within the bounds of (8). The sources described by the model with $\Omega_M = 1$ are shown in Group 3. They have positive relative deviations and their values agree with (8) as well. In Group 4 one can find four supernovae with coordinate distances which are not described by any above mentioned model even with the regard for observation errors. The values $\delta a/\langle a\rangle$ for two of them (see Table 1) satisfy the estimations (8). For SNe 1997ck (Group 1) and 1995ar (Group 4) the values of relative deviations with regard for uncertainty of measurements [17] (if one takes the lowest value) are equal to $\delta a/\langle a\rangle = -0.048$ and $\delta a/\langle a\rangle = -0.061$ respectively. The supernova 1997K at $z = 0.592$ is characterized by too sharp negative relative deviation even in comparison with the largest possible fluctuations of the scale factor. If one takes into account uncertainty of measurements and accept for distance the value $H_0 r(z) = 0.651$ [17] then the corresponding deviation $\delta a/\langle a\rangle = -0.17$ will still exceed the relative deviation at $\Delta t = 3$. The same analysis one can make for RGs as well.

Thus the observed faintness of some SNe Ia can in principle be explained by the logarithmic-law dependence of coordinate distance on redshift in generalized form (9) which takes into account the fluctuations of scale factor about its average value. These fluctuations can arise in the early universe and grow with time into observed deviations of the coordinate distances of separate SNe Ia at the high redshift. They produce accelerating or decelerating expansions of space subdomains containing such sources whereas the universe as a whole expands at a steady rate.

4 Concluding remarks

In addition to the prediction about the steady-speed expansion of the universe as a whole (at the same time the accelerating or decelerating motions of its subdomains remain possible on a cosmological scale as it is shown in Sect. 3) the quantum model allows an increase of quantity of matter/energy in matter dominated universe according to (3). If the mass m of elementary excitations of the scaler field remains unchanged during the expansion of the universe, then the increase of M can occur due to increase in number s of these excitations. But the increase in s does not mean that a quantity of observed matter in some chosen volume of the universe increases. According to the model proposed in Refs. [19, 20] the observed "real" matter (both luminous and dark) is created as a result of the decay of excitations of the scalar field (under the action of gravitational forces) into baryons, leptons and dark matter. The undecayed part of them forms what can be called a dark energy. Such a decay scheme leads to realistic estimates of the percentage of baryons, dark matter and energy in the universe with $\langle a\rangle \gg 1$ and $M \gg 1$. Despite the fact that the quantity of matter/energy can increase, the mean total energy density decreases and during the expansion of the universe mainly the number of elementary excitations of the scalar field increases. Their decay probability is very small, so that basically only

the dark energy is created. These circumstances can explain the absence of observed events of creation of a new baryonic matter on a cosmologically significant scale.

The proposed approach to the explanation of observed dimming of some SNe Ia may provoke objections in connection with the problem of large-scale structure formation in the universe, since the energy density $\langle\rho\rangle$ in the form (4) cannot ensure an existence of a growing mode of the density contrast $\delta\langle\rho\rangle/\langle\rho\rangle$ (see e.g. Refs. [16, 18, 21]). As we have already mentioned above in Sect. 2 the density $\langle\rho\rangle$ (4) describes only homogenized properties of the universe as a whole. It cannot be used in calculations of fluctuations of energy density about the mean value $\langle\rho\rangle$. Under the study of large-scale structure formation one should proceed from the more general expression for the energy density (2). Defining concretely the contents of matter/energy M, as for instance in the model of creation of matter mentioned above, one can make calculations of density contrast as a function of redshift. The problem of large-scale structure formation is one of the main problems of cosmology (see e.g. Refs. [16, 22]). It goes beyond the tasks of this paper and requires a special investigation. The ways of its solution in the quantum model are roughly outlined in Ref. [12].

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